Long-term forecasting of the COVID-19 epidemic

Dynamic Causal Modelling, UCL, UK

- **The real-time estimate of the R-number is 1.10 (credible interval from .62 to 1.57) on 16 June 2021.** This reproduction ratio should fall to about one in the next four weeks.
- **The current estimate of the efficacy of vaccination stands at 83.0% (credible interval from 81.9 to 84.1%).** This efficacy pertains to the prevention of serious (systemic) illness.
- **Daily deaths are predicted to rise slowly — to about 20 deaths per day — over the summer.** And may show a winter peak of about 80 deaths per day.
- **These predictions rest upon a gentle and prevalence–dependent unlocking**. A final lifting of restrictions is anticipated on 23 July 2021.
- **The basic reproduction number R_0 is currently estimated to be 5.07.** This corresponds to a 31% increase in transmission risk, relative to the average since 1 February 2020.

These headlines furnish a national picture of the epidemic and therefore obscure important regional variations. For a more detailed picture — at the level of lower tier local authorities — please see the accompanying local dashboard.

Disclaimer: *the modelling and accompanying estimates are reported in these pages for purely academic (open science) purposes. This modelling has not been commissioned. In particular, dynamic causal modelling is not commissioned by the Independent SAGE (on which Prof Friston serves as a panellist). The independent SAGE does not commit to — or engage in — any particular modelling initiative.*

These long-term forecasts are based upon a dynamic causal model (DCM) of viral transmission and mitigated responses. This particular (age-stratified) model is equipped with a vaccination state that affords sterilising immunity (i.e., precludes transmission and clinical susceptibility). Immune efficacy is modelled as the probability of developing a severe illness when vaccinated, relative to someone who is not vaccinated.

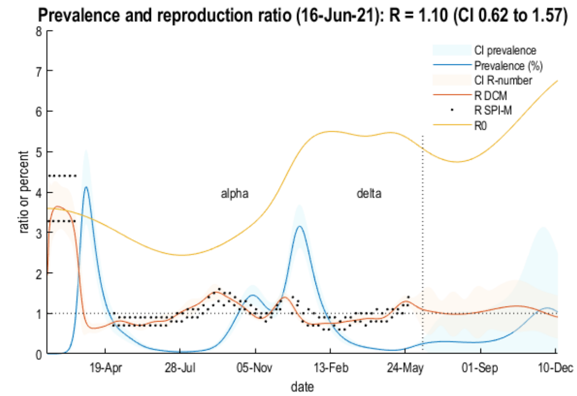
The DCM generates various data that quantify the progression of the epidemic, including the number of reported (first) vaccinations. These data are used to estimate the model parameters controlling contact rates, transmission risk and periods of infectiousness using standard variational procedures. Crucially, these variables are themselves time-dependent and depend upon mitigating responses, modelled as the (prevalence-dependent) probability of moving from low to high contact rate locations (e.g., from home to the workplace). The data that informs these estimates include daily positive tests, reported deaths within 28 days of a positive PCR test, certified deaths disaggregated by age and place of death, hospital admissions, contact rate proxies, such as car use and Google mobility data, and so on. Please see the national dashboard for a more detailed report of the data fitting—and other epidemiological variables—upon which the long-term forecasts are based.

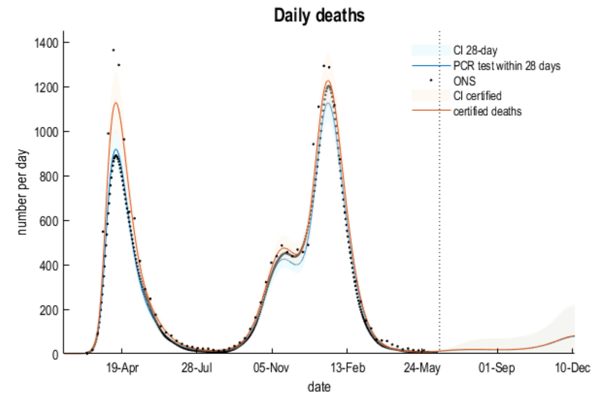
Much like long-term weather forecasts, the ensuing predictions should not be over interpreted because there is an inherent (although quantified) uncertainty about underlying epidemiological and socio-behavioural variables. These reports will be released on a weekly basis so that people can see how the predictions change — and uncertainty resolves — as time progresses and more data are assimilated.

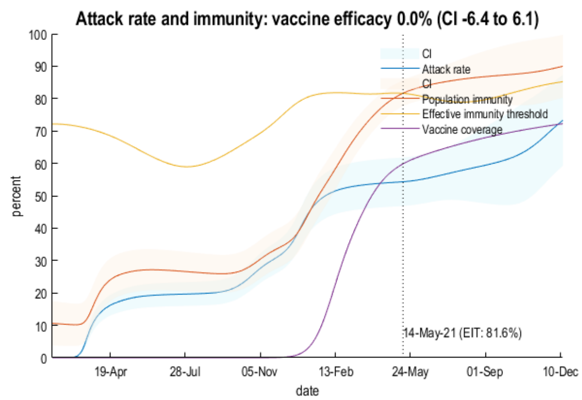
Because the DCM is, effectively, an amalgamation of a conventional epidemiological model and an agent-based behavioural (and testing) model it predicts mitigating responses to changes in community transmission. These DCM predictions are the **most likely outcomes** given our responses to date. In other words, it does not rely on any assumptions about future scenarios (e.g. roadmaps for unlocking). This complements — and contrasts with — SPI-M projections of **reasonable worst-case scenarios** that assume a particular sequence of interventions. Generally, the most likely *predictions of mitigated responses* — i.e., what is likely to happen — are more optimistic than worst-case *projections of unmitigated* responses — i.e., what could happen.

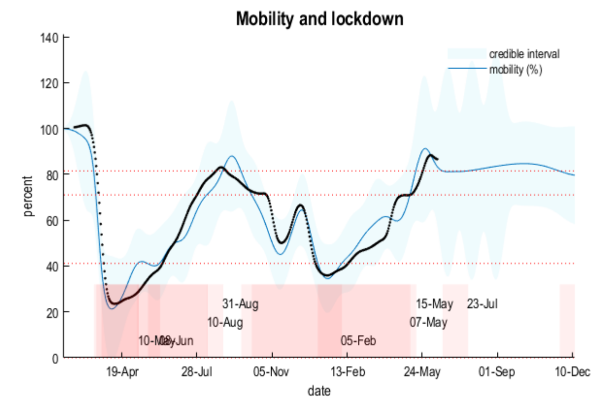
Summary graphs

In the summary graphs below, the lines and shaded intervals correspond to predictions and 90% credible intervals, while the black dots are (smoothed) data upon which the estimates are based.









Prevalence and reproduction ratio: this panel provides a forecast of (i) the **prevalence of infection** and (ii) the reproduction ratio or **R-number** (blue and orange lines, respectively) with their accompanying confidence intervals (shaded areas). These forecasts are based upon parameters estimated from the data up until the reporting date (the vertical line). The data include GOV.UK estimates of the R-number, which are shown for comparison with the DCM estimates. The **basic reproduction ratio** (R0 – yellow line) can be read as the R-number in the absence of any mitigating reductions in contact rates (under the simplifying assumption that the mean period of infectivity is constant). This reflects fluctuations in transmission risk due to seasonality effects and viral mutations. The 'alpha' and 'delta' indicate when the alpha and delta variants were introduced to the UK.

The DCM estimate of the R-number is based upon a generative model (i.e., a real-time estimate using data assimilation). The corresponding consensus estimates from the SPI-M are based upon retrospective (e.g., Bayesian regression) analysis of recent data and are therefore treated as a lagged estimator. The black dots correspond to the GOV.UK (SPI-M consensus) estimates moved backwards in time by 16 days from their date of reporting.

Attack rate and immunity: this panel shows long-term forecasts of **attack rate, population or herd immunity** and the percentage of people who have been vaccinated. In addition, an estimate of the **effective immunity threshold** is provided based upon simplifying (SIR) assumptions (yellow line). Based upon the changes in testing, death rate and other data, one can estimate the efficacy of vaccination. The attack rate corresponds to the number of people who have been infected since the onset of the outbreak (blue line). This can be supplemented with a small proportion of the population that is estimated to have pre-existing immunity (e.g., mucosal immunity or cross immunoreactivity with other SARS viruses), shown in red. The combination can be read as the herd or population immunity.

The effective immunity threshold is based upon the effective reproduction ratio under pre-pandemic contact rates. The reproduction ratio corresponds to the product of the contact rate, transmission risk and mean infectious period. Note that the effective immunity threshold fluctuates. This reflects the fact that transmission risk changes with time. In this model, transmission risk is modelled as a seasonal fluctuation multiplied by smooth (increasing) function of time. A fluctuating transmission risk accommodates changes in transmissibility (e.g., due to viral evolution) that is contextualised by seasonal variations in transmission (e.g., due to changes in temperature, humidity, socialising outdoors and the propensity for aerosol transmission). The vertical line shows when the population immunity first exceeds the effective immunity threshold.

Daily deaths: this panel shows fatality rates as assessed by patients who died within 28 days of positive PCR test and people who died from certified COVID-19. The former represents an underestimate of COVID-related mortality, where the degree of underestimation depends upon testing rates. The discrepancy is adequately modelled by evaluating the probability of succumbing to COVID-19 and having had a positive PCR test within 28 days.

Mobility and lockdown: a long-term forecast of locking and unlocking, based upon car use as quantified by the Department of Transport and - in this graph - Google mobility data. These measures of mobility are expressed in terms of the percentage of pre-pandemic levels. The expected mobility has been thresholded at three levels to illustrate different levels of lockdown. The dates on the lower (graded pink) bar annotate a transition from a more restrictive level of mobility to a less restrictive level. Forecasts of mobility are based upon underlying contact rates that depend upon the prevalence of infection, which are then modulated with a smooth function of time (parameterised with Fourier coefficients).

This dynamic causal model includes age-stratification into three groups (below the age of 25, between 25 and 65 and over 65 years of age). The contact rates within and between the three groups (for high and low contact rate locations) are estimated from the data, under mildly informative lognormal shrinkage priors. Please see the following technical report for further technical details.

Changes since last report:

- Vaccine efficacy re-parameterised in terms of (i) effectiveness of preventing viral transmission and (ii) serious (systemic) illness. This allows for vaccinated people to become infected (and symptomatic) but with a reduced probability of becoming infectious (or seriously ill).

- Age-specific loss of seropositivity, following natural infection has now been included.
- Priors relaxed over the loss of vaccine-induced seropositivity and seronegative (e.g., T-cell mediated) immunity.

Software note: The figures in this report can be reproduced using annotated (MATLAB) code available as part of the free and open source academic software SPM (https://www.fil.ion.ucl.ac.uk/spm/), released under the terms of the GNU General Public License version 2 or later. The routines are called by a demonstration script that can be invoked by typing `>> DEM_COVID_UK` at the MATLAB prompt.

Data sources: (also available as CSV files)

https://coronavirus.data.gov.uk
https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/datasets/coronaviruscovid19infectionsurveydata
https://covid.joinzoe.com/data#levels-over-time
https://www.gov.uk/guidance/the-r-number-in-the-uk#contents
https://www.gov.uk/government/statistics/transport-use-during-the-coronavirus-covid-19-pandemic
https://www.google.com/covid19/mobility/

Peer-reviewed references [1-3] and **archival papers** [4-11]

1. Friston, K.J., et al., Second waves, social distancing, and the spread of COVID-19 across America. Wellcome Open Research, 2020. 5(103): p. 103.
2. Friston, K.J., et al., Dynamic causal modelling of COVID-19. Wellcome Open Research, 2020. 5(89): p. 89.
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4. Moran, R.J., et al., Using the LIST model to Estimate the Effects of Contact Tracing on COVID-19 Endemic Equilibria in England and its Regions. medRxiv, 2020.
5. Friston, K.J., G. Flandin, and A. Razi Dynamic causal modelling of mitigated epidemiological outcomes. 2020. arXiv:2011.12400.
6. Daunizeau, J., et al., On the reliability of model-based predictions in the context of the current COVID epidemic event: impact of outbreak peak phase and data paucity. medRxiv, 2020.
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8. Gandolfi, D., et al., Dynamic causal modeling of the COVID-19 pandemic in northern Italy predicts possible scenarios for the second wave. medRxiv, 2020: p. 2020.08.20.20178798.
9. Moran, R.J., et al., Estimating required 'lockdown' cycles before immunity to SARS-CoV-2: Model-based analyses of susceptible population sizes, 'S0', in seven European countries including the UK and Ireland. medRxiv, 2020: p. 2020.04.10.20060426.
10. Friston, K.J., et al., Viral mutation, contact rates and testing: a DCM study of fluctuations. medRxiv, 2021: p. 2021.01.10.21249520.
11. Friston, K.J., et al., Tracking and tracing in the UK: a dynamic causal modelling study.

- Report on DCM long-term forecasting - 2nd February 2021
- Report on DCM long-term forecasting - 6th February 2021
- Report on DCM long-term forecasting - 14th February 2021
- Report on DCM long-term forecasting - 21st February 2021
- Report on DCM long-term forecasting - 27th February 2021
- Report on DCM long-term forecasting - 7th March 2021
- Report on DCM long-term forecasting - 14th March 2021
- Report on DCM long-term forecasting - 20th March 2021
- Report on DCM long-term forecasting - 27th March 2021
- Report on DCM long-term forecasting - 4th April 2021
- Report on DCM long-term forecasting - 11th April 2021
- Report on DCM long-term forecasting - 18th April 2021
- Report on DCM long-term forecasting - 24th April 2021
- Report on DCM long-term forecasting - 4th May 2021
- Report on DCM long-term forecasting - 8th May 2021
- Report on DCM long-term forecasting - 17th May 2021
- Report on DCM long-term forecasting - 22nd May 2021
- Report on DCM long-term forecasting - 1st June 2021
- Report on DCM long-term forecasting - 5th June 2021
- Report on DCM long-term forecasting - 16th June 2021